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LEO Orbit Surface Charging and Its Relationship to Environment, Vehicle Geometry, and Ionospheric Conditions

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14. ABSTRACT

Ungrounded surface materials on the exterior of low- to medium-altitude and medium- to high-inclination satellites can become charged in the auroral electron environment at high latitudes. The orientation of such surfaces will present different aspects relative to the satellite-sun line and the satellite velocity vector. Such surfaces can be both in shadow and in the satellite wake at the same time, which enhances the chances of charging in the dusk to pre-noon sector of the auroral oval, depending on plasma density and lighting conditions at the satellite altitude and inclination. It is recommended that all surfaces be conductors if surface charging and associated electrostatic discharge (ESD) are to be avoided. Otherwise, the satellite system should be designed to tolerate the surface ESD that will occur.

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Charging, Space environment, Low altitude

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Figures

The primary purpose of this note is to discuss the concept of Low Earth orbit (LEO) auroral environment caused surface charging and to address in a limited way how it differs from high altitude charging such as that experienced by geosynchronous orbit, high Earth Orbit (HEO) or Global Positioning System (GPS) satellites.

The question of whether or not a surface differentially charges depends on the surface conductivity of the exterior material and whether it is grounded to the structure. If the surface acts like an insulator or is ungrounded, its charging will depend upon the ion density in the neighborhood of the surface, whether a surface charging environment is present, and whether the surface is illuminated or in shadow. Much of the discussion below can be generally applied to any LEO satellite in <2000 km altitude orbits with inclinations that cause the orbit to traverse the auroral regions. At higher altitudes, the auroral environment may be sufficiently different that it requires a separate study.

The LEO charging environment occurs in the auroral zones where electrons are accelerated down magnetic field lines from higher altitudes (>2,000 km) at moderately high latitudes at LEO altitudes (Croley et al., 1978; Fennell, 1985; Fennell et al., 2002). These accelerated electrons can charge dielectric surfaces or isolated conductors if they impinge on them. The first question always is whether these electrons can reach the surfaces. That depends on the orientation of the local magnetic vector relative to the spacecraft's position and attitude and the angular distribution of the electrons relative to the magnetic field. Figure 1 shows that the angular distributions of the accelerated electrons is very isotropic except in the upcoming "loss cone." Since the charging electrons have sizable

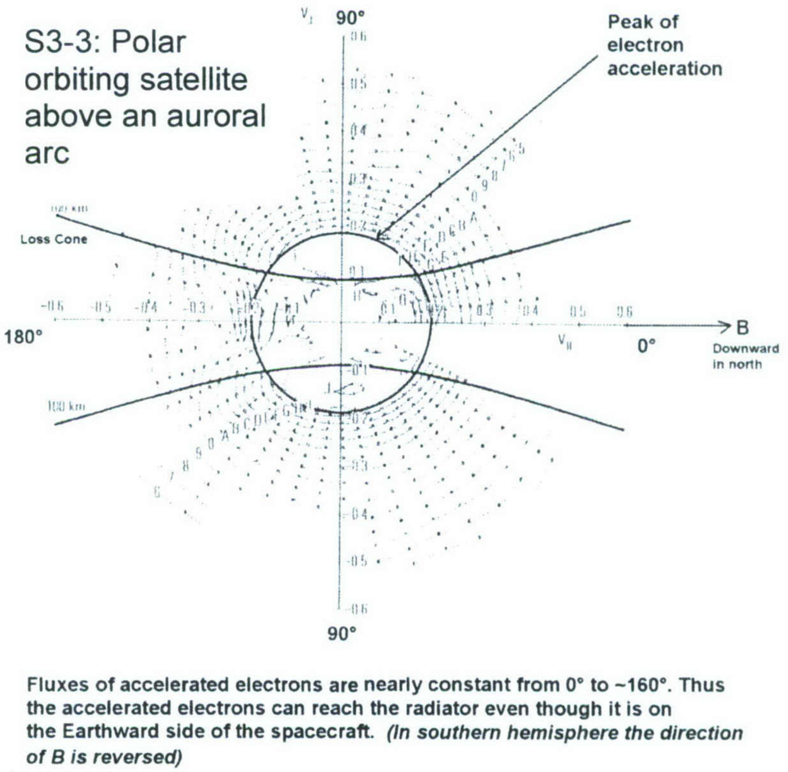

Figure 1. Electron velocity space distributions in the middle of an auroral arc showing the nearly isotropic electrons outside the acceleration circle with a loss cone near 180° pitch angle.

gyroradii ($\geq$ 3 m for 1-keV electrons), those on a magnetic field line adjacent to the spacecraft can reach the surfaces as they gyrate around their guiding field line (Figure 2). In the auroral regions, the magnetic field lines are close to radial (i.e., along the nadir-zenith direction), and the nearly isotropic charging electrons can reach all surfaces.

The statistics for auroral charging were based on a 12-year study of charging on seven Defense Meteorological Satellite Program (DMSP) spacecraft flying in sun-synchronous orbits (~99° inclination) at 840 km with ascending nodes near 1800 and 2000 solar local time (Anderson, 2000; Anderson and Koons, 1996). Generally, charging occurred on the DMSP spacecraft when the satellite was in darkness, the ambient plasma density was $<10^4/cm^3$, and there was large flux of energetic electrons with energies above 5 keV in the auroral regions (Anderson, 2000; Anderson and Koons, 1996). These requirements were met most often during solar minimum (the minimum in the 11-year solar cycle) at winter solstice when the solar UV illumination (and subsequent ionization) was at a minimum. This is shown in Figures 3 and 4. Figure 3 shows the distribution of over 1600 DMSP charging events (defined as an auroral crossing in which the spacecraft frame charged to over 100 V negative) between 1989 and 2001. The sunspot number is included to relate the events to where they occurred in the solar cycle. Figure 4 shows the corresponding ionospheric density at DMSP in the northern and southern auroral zones. The ionospheric density was clearly the smallest at the minimum in the solar cycle near winter solstice.

The low ionospheric density requirement will be met more often at higher altitudes than it was on DMSP. The density will be ~50% lower at 1350 km than it was at DMSP. The cold background plasma ions have thermal velocities much slower than the satellite velocity. As a result, a LEO satellite speeds through them, collecting them as a "ram ion population" on the "front" surface of the vehicle, leaving a very low density "wake" nearly devoid of ions behind it. Thus, the surfaces facing opposite to the satellite velocity vector receive very little ion flux to counteract the electron charging current. So the motion of the satellite creates a high plasma density on the ram side and a low plasma density on the wake side of the satellite surfaces. Orbital cuts that show the most charging are those

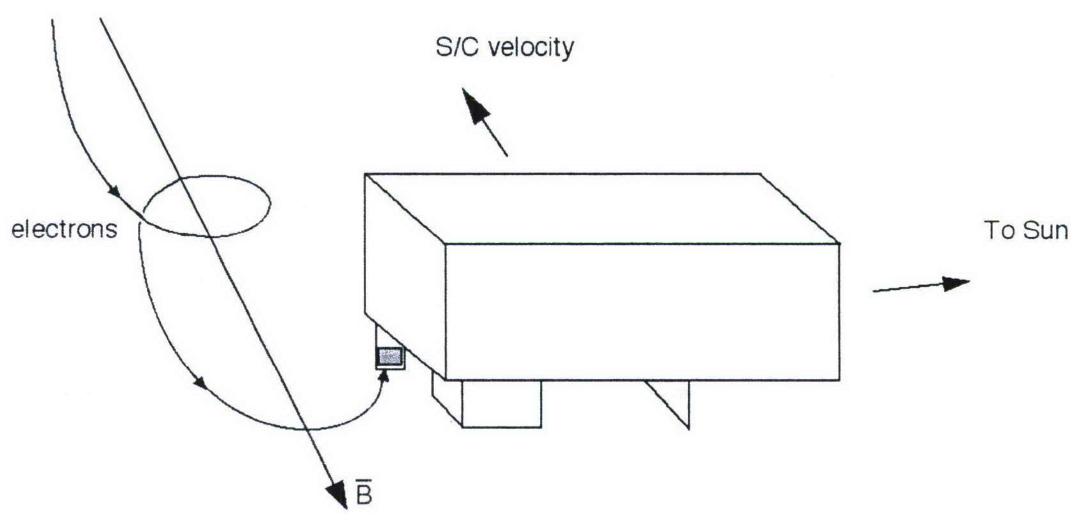

Figure 2. Auroral electrons spiral Earthward but can reach the shadowed surface from magnetic-field lines adjacent to the spacecraft.

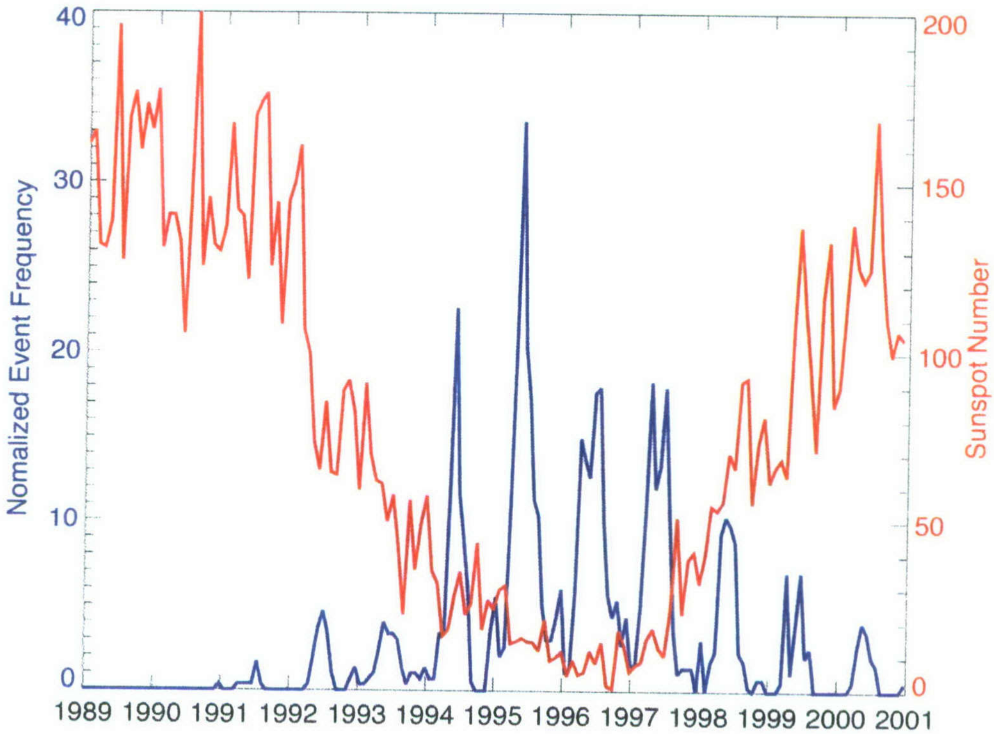

Figure 3. Number of DMSP charging events (normalized to the number of satellites) per 25 days over 12 years and the sunspot number.

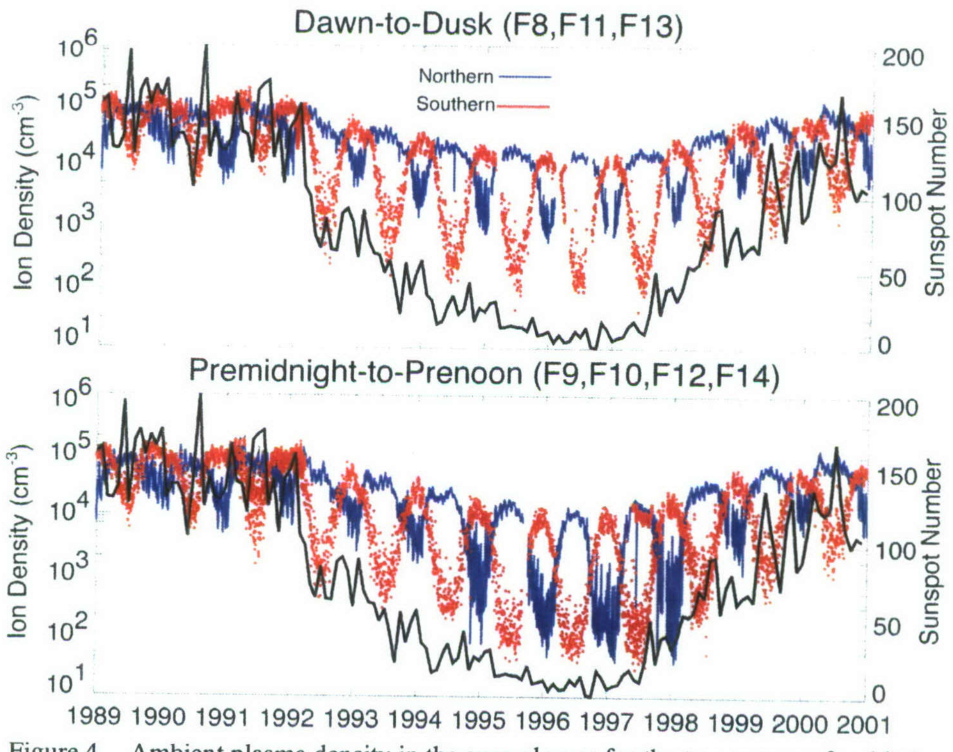

Figure 4. Ambient plasma density in the auroral zone for the two spacecraft orbital planes, separated by hemisphere, and the sunspot number.

where a satellite surface is in Earth shadow, or is vehicle-shadowed and at the same time is on the wake side. In general, those conditions can occur as a satellite passes through the dusk-to-dawn auroral regions.

The acceleration of auroral electrons occurs within events known as substorms, which generate intense auroral arcs. These are very strong precipitation events that occur during geomagnetically active periods and occur only a few percent of the time, depending on solar activity. For DMSP they occurred primarily in the pre-midnight to dawn sectors. Figure 5 shows the magnetic local time (MLT) and magnetic latitude (MLAT) distribution of charging events on the DMSP spacecraft at 840 km. Also plotted are two days of LEO orbit tracks (separated by about one month), selected as the worst-case conditions for two different orbital plane local-time locations. Since auroral arcs are nominally aligned with geomagnetic latitude, the LEO spacecraft will stay the longest in the auroral arcs on orbits that skim along iso-magnetic latitude contours in the pre-midnight to midnight sectors. These are also the scenarios in which the spacecraft orientation provides the optimum conditions for charging, as mentioned in the previous paragraph. *(Note that the energetic auroral electron conditions at 2000 km are nearly identical to those at 840 km.)* The duration of a single auroral charging interval can approach two minutes at DMSP altitudes and would be somewhat more at higher altitudes. Multiple auroral charging intervals can occur within a single polar traversal if the satellite trajectory nearly matches the latitude and local-time profile of the auroral arcs (see Akasofu, 1981, for examples of auroral forms and positions).

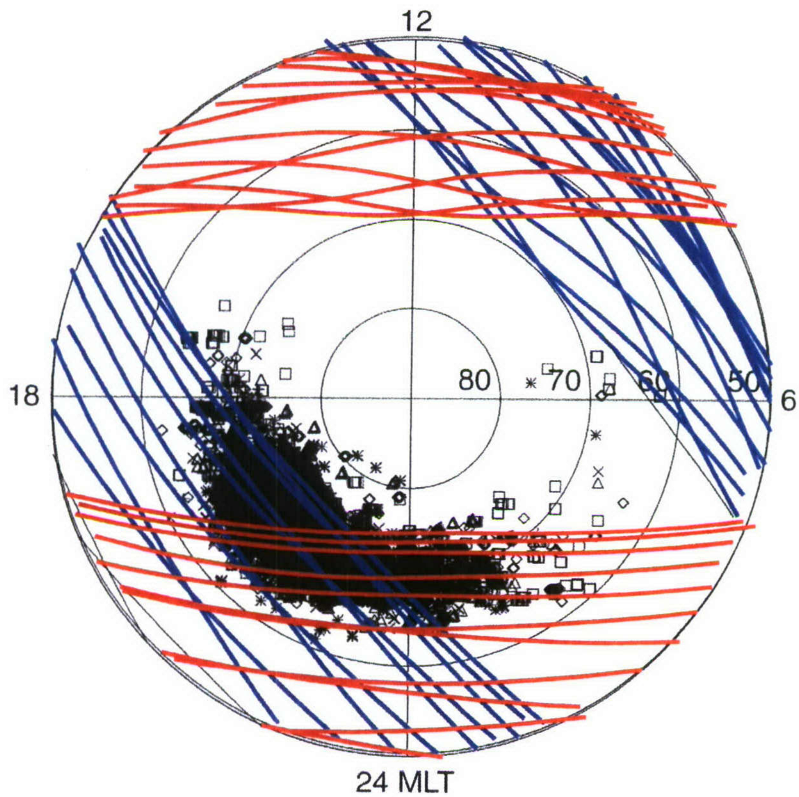

Figure 5. Magnetic local time (MLT) and magnetic latitude MLAT) distribution of DMSP charging events with two days of a LEO satellite's orbit tracks overlaid.

Figure 6 shows the geographic location of some DMSP charging events with a day of LEO orbit tracks overlaid. The LEO satellite will encounter the auroral regions where the charging occurs when it is over Canada and south of Australia for the orbit parameters used. This is because the auroral regions (ovals) are aligned with geomagnetic latitude (not geographic) and the Earth's magnetic field axis is offset from its spin axis by ~12° (Akasofu, 1981). The separation between geomagnetic latitude and geographic latitude is greatest when the orbit passes through Canadian and Australian longitudes at high latitudes. Note that the asymmetry between the number of events in the southern and the northern hemispheres in Figure 6 is a function of the sun-synchronous nature of the DMSP orbit and will not apply to all LEO satellite orbits. Note also that if the orbital inclination was increased, the probability of being in the auroral charging environment increases rapidly with increasing inclination. This would be true of satellites in moderately high-latitude LEO orbits irrespective of their altitude (up to 2000 km).

In high-altitude orbits, such as GPS, HEO (most of its orbit), and geosynchronous satellites, the charging environment can extend over very large regions in altitude and local time (e.g., Fennell and Roeder, 2007; Fennell et al., 2000). When the charging environment exists, there is not a cold dense ion population present; i.e., the low ion density requirement noted above is always met and there is not a ram-wake effect since the ions that do exist have high velocities compared to the satellite velocity. The electron and ion populations that make up the charging environment are essentially isotropic. Thus, the primary issues that control charging for high-altitude satellites are the mean energy and density of the electron population and the sunlit and shadow condition of the satellites surfaces. While self-shadowing can occur on these high-altitude satellites, exacerbating the charging, there is no ram-wake effect such as occurs in LEO orbits.

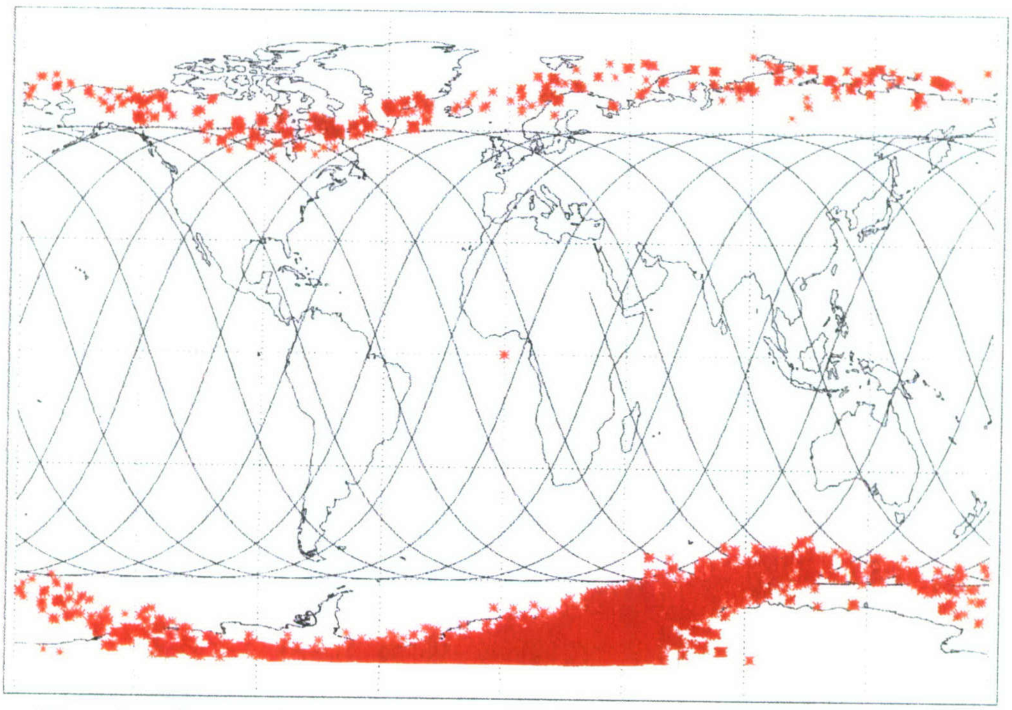

Figure 6. Geographic location of the DMSP charging events with a day of a LEO satellite's orbit tracks overlaid.

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